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HOT FRACTURED ROCK (HFR) GEOTHERMAL DEVELOPMENT, COOPER BASIN, AUSTRALIA

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SUMMARY – Geodynamics is close to conclusion of Stage One of its Hot Fractured Rock geothermal program in Australia's Cooper Basin. An injection well to 4,421 m has been drilled. This discovered very high overpressures in the HFR resource, equivalent to 345 bar at surface. The world's largest enhanced geothermal reservoir was created by hydraulic stimulation. After initial successful flow testing, the project has been delayed by a blockage in the production well Habanero #2. Completion of Stage One is scheduled for 2007 after drilling of a third well, Habanero #3.

1. INTRODUCTION

Since commencement of field activities in Geothermal Exploration License (GEL) 98 in early 2003, Geodynamics has:

- Drilled Habanero #1 injection well to a depth of 4,421 m, and established the temperature, pressure and fracture conditions in the target granitic basement rocks.
- Created the world's largest enhanced geothermal heat exchanger from a single well (Habanero #1), by high pressure hydraulic stimulation and supported by the acoustic monitoring network. The heat exchanger is uniquely of near-horizontal extent.
- Targeted and drilled Habanero #2 production well to a depth of 4,358 m into the enhanced geothermal heat exchanger.
- Carried out initial flow and injection testing of the heat exchanger including demonstrating flows of up to 25 kg/s and surface production temperatures of 210°C for a power output of 15 MWthermal.
- Developed multiple heat exchanger reservoirs.
- Enhanced and enlarged the existing heat exchanger to an arial extent of 4 km^2, 50% larger than the original development.
- Modelled the reservoir performance using provisional data characteristics showing a slow temperature drawdown of 40°C over 50 years.

2. CONCEPT OF HFR GEOTHERMAL ENERGY EXTRACTION

Hot Fractured Rock (HFR) geothermal energy is a renewable energy prize which was first recognised by the Los Alamos National Laboratory in New Mexico in the 1970s. The concept was initially known as Hot Dry Rock (HDR).

HFR involves circulating water through a permeable rock body of high temperature. Access to the rock body is through a network of vertical injection and production wells spaced on a regular grid.

Research projects funded for the most part by Governments were developed, initially in the US (New Mexico), followed by the UK (Cornwall), Japan (Hijiori and Ogachi), France (Soultz), and more recently Switzerland (Basel) and Germany (Bad Urach and Gross Schönebeck). All but Gross Schönebeck were operated in granitic rocks known to have natural fracture systems.

Granite is the ideal rock to perfect the process because it commonly has families of cooling-related natural fractures that extend many hundreds of metres, and because granite commonly forms masses with homogeneous rock properties that extend over hundreds of cubic kilometres. Granites also produce their own radiogenic heat and are rather benign geochemically.

Much was learnt from the early projects including the fact that existing natural joints or fractures in granite developed permanent fracture permeability enhancement when fluid was injected at high enough pressures to slip fracture planes accompanied by the emission of acoustic waves. This hydraulic stimulation process has been the basis of all the projects to date with progressive flow of the fluid monitored by tracking the acoustic emissions with a network of sensors. The resulting zone of enhanced permeability represents the underground heat exchanger or reservoir.

Another significant outcome of the early projects was to show that the shape of the heat exchanger is dependent on the orientation of the three dimensional rock stress field within the rock mass. In most, if not all, volcanic areas of the world, the minimum principal stress orientation (S3) is approximately horizontal. Without this condition the volcanic activity would not have been present in the first place, since low horizontal stresses are required to allow magma to rise into the upper crust. Thus in volcanic areas of the world, and in environments with strike-slip stress fields, a man-made heat exchanger tends to be oriented vertically. Such a geometry is not ideal for development of large volume heat exchangers and interconnected multi-well systems. Water loss from a producing HFR system can also be a serious problem in regions with S3 horizontal since such environments tend to be intrinsically more "leaky".

In many non-volcanic areas of the world, particularly in ancient cratonic areas devoid of volcanic activity, such as the Baltic and Canadian Shields and much of the basement parts of the Australian continent, S3 is vertical. Thus we have the dichotomy of, on the one hand, poorly oriented heat exchangers forming in volcanic areas where the rock temperature might be high, while, on the other hand, optimally oriented heat exchangers tend to form in non-volcanic areas where the rock temperature is generally likely to be low at reasonable drilling depths.

The difficulty then arises of finding high temperature rocks in non-volcanic regions. Again granite rocks play a major role in this process. Many granites have slightly elevated abundances of radiogenic elements that result in continued self-heating of the rock mass. These granites are known as high-heat-production or HHP granites. Provided the escape of this heat is hindered by thermal blanketing of overlying rocks with low thermal conductivity this heat can build up significantly over a few million years. For example, an HHP granite that is buried at a depth of around 3-4 km by low conductivity sediments such as shale and coal measures can heat up to temperatures exceeding 200°C. These depths are easily accessible by typical drilling rigs operated for the oil industry.

3. HFR EXPLORATION IN SOUTH AUSTRALIA

It was with these understandings that the South Australian Government introduced geothermal legislation into the revised Petroleum Act in 2000. All the conditions for optimal development of HFR resources seemed to be present in the central, deepest part of the Cooper Basin near Innamincka in NE South Australia. In this area prior oil and gas exploration wells had been drilled through low thermal conductivity sediments around 3.5 to 3.7 km thick and intersected what gravity and seismic data showed to be a large body of HHP granite in the basement below the sediments. Temperatures in excess of 200°C were measured near the bottom of some of these wells.

The hot buried granite at Innamincka represents the only fully delineated HFR geothermal energy target in Australia to date. The temperature resource contained within this granite is both well understood and well characterised, at least in its shallower levels.

Geodynamics now holds Geothermal Exploration Licenses (GEL's) 97, 98 99 and 211 in South Australia. Each of these licenses covers an area of approximately 500 square kilometres.

4. PRE-EXISTING GEOLOGICAL INFORMATION OF THE CENTRAL COOPER BASIN

The geological information for the Cooper Basin derived from over 4 decades of oil exploration includes tens of thousands of kilometres of seismic traverses, and over 3,000 wells drilled. From this information the following has been established:

- The depth to basement in the deeper parts of the Cooper Basin, in an area known as the Nappamerri Trough, is approximately 3.5-4.5 km;
- In the Nappamerri Trough, geothermal gradients of 55-60°C/km had been measured, consistently higher than normal;
- The Nappamerri Trough exhibited a gravity low that could not be explained by the additional thickness of sediments alone indicating it to be underlain by a large granite body;
- A number of drillholes into basement in the Nappamerri Trough area had intersected granite and chemical analyses indicated that this granite is HHP;
- Modelling suggests that the granite underlies the whole of the gravity low of approximately 1,000 km^2. The modelled thickness of the granite is 10 km;
- Stress conditions in the Nappamerri Trough indicated an overthrust stress environment. This means S3 is vertical, in common with many basement areas of the Australian continent, but different to shallower parts of the Cooper Basin to the NW;
- Overpressures had been observed towards the base of the sedimentary sequence in deep wells in the Nappamerri Trough, but the permeability of the sedimentary units was too low for the true overpressures to be established.

5. DRILLING OF HABANERO-1

Geodynamics' first well in the Stage One program, Habanero #1 is located 450 m WSW of the McLeod #1 well, an older petroleum exploration well. McLeod #1 was drilled into granite basement at 3,747 m depth in 1983, and a temperature of 230°C was recorded.

Habanero #1 was completed in October 2003 to a total depth of 4,421 m. The well was designed for use as an injection well. The basement granite was initially intersected at 3,668 m, and seven inch casing was set at 4,135 m. Logging with a borehole imaging tool prior to setting the seven inch casing showed that a set of shallowly dipping fractures intersected the well less than 10 m above the depth of the seven inch casing shoe.

During drilling operations in the six-inch section, several events involving mud losses and influxes required well killing with high weight drilling mud. From these events it was determined that the natural fractures in the granite were over-pressured by more than 5,000 psi (34.5 MPa).

The high overpressures and apparent abundance of water were a surprise and invites the conclusion that there could have been weak, but considerable natural seismic activity in recent geological times associated with the development of the overpressures. Such activity would have created enhanced fracture porosity and permeability in the region where the overpressures now exist.

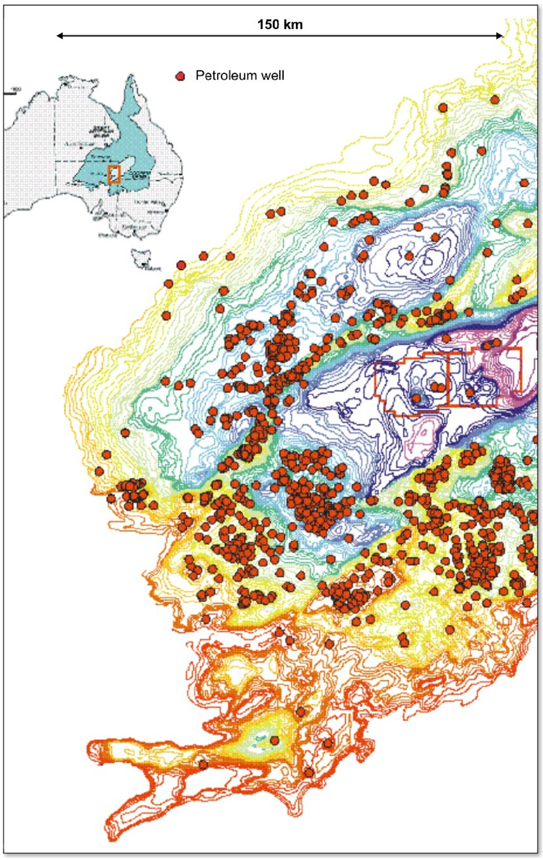

Figure 1. Contours of the maximum depth of the Cooper Basin in NE South Australia (shallowest in red and deepest in blue) based on observations from existing petroleum wells (red points). The deepest parts are 3.5-4.5 km deep. The locations of the Geodynamics GEL97 and 98 geothermal leases are shown as heavy red lines. . Map data courtesy of Primary Industry and Resources, South Australia.

A 4½ inch tubing completion was installed in the well to a depth of 3,091 m to cover the more vulnerable parts of the seven inch casing.

6. GRANITE COMPOSITION

The granite intersected in Habanero #1 is a medium to coarse grained white two-mica granite with a colour index of around three. The granite is cut by many dykes and veins of white aplite or alaskite. Biotite mica in the granite is almost completely altered to chlorite indicating pervasive hydrothermal alteration. Tourmaline is a common accessory mineral. Much of the feldspar is altered.

The granite contains around 75% SiO2 and over 5% K2O. The heat productivity is 7-10 µwatts/m3 as determined by the Rybach equation.

7. HYDRAULIC STIMULATION OPERATIONS IN HABANERO-1

Geodynamics, with the assistance of Japanese seismic experts, set up a network of eight acoustic monitoring wells covering an area of 50 km2 around Habanero #1. The main stimulation commenced on 30 November 2003, with step injection rates of 5, 7 and 9 barrels per minute (bpm) (13, 18.5 and 24 l/s) over several days each, until a cumulative volume of 16,350 m3 had been injected by 9 December.

Based on micro-acoustic locations of more than 11,700 events, the estimate of stimulated volume was 0.7 km3, significantly greater than expected based on previous overseas projects. This volume is the largest developed so far from a single stimulation in an HDR or HFR project, and probably results from the extensive nature of the sub-horizontal fractures and to the reservoir fluid overpressure.

Overall stimulation operations ceased on 22 December 2003 with more than 23,000 m^3 of water injected, at surface pumping pressures up to 9,800 psi (67.5 MPa).

8. LOCATION FOR THE PRODUCTION WELL, HABANERO #2

The best location for the production well was determined with the assistance of experts from Japan and Germany. The location chosen, 500 m to the southwest of Habanero #1 was based on:

- early acoustic development in that direction;
- absence of upwardly directed growth;
- high event and energy density of the acoustic emissions;
- apparent multiple layers of events indicating multiple fracture layers dipping gently to the west or southwest;
- stress modelling indicating shallowly dipping (25°) structures are the most favourable for slip.

9. DRILLING OF HABANERO-2

The well casing layout of Habanero #2 is similar to Habanero #1; however the functional requirement to tolerate both high-pressure injection and high temperature production demanded different well construction and cementing strategies. Accordingly, the surface and intermediate casings were pre-tensioned prior to cementation and all casing strings (including the seven inch production casing) were cemented to surface. The wellhead and Christmas tree were designed for cold water injection at 10,000 psi (68.9 MPa) and production at 250°C and 7,500 psi (51.7 MPa). The seven inch production casing is designed to act as the primary flow conduit, which avoids the need for a completion.

Habanero #2 was spudded on 10 July 2004 with a target depth of 15,000 ft (4,572 m). The well was drilled to the granite (3,681 m) by 5 September, and the seven inch casing was set and cemented at 3,927 m with nitrogen foam cement on 16 September, on time and on budget.

The evidence from the drilling of Habanero #1 and the stimulation indicated that the fracture system was at a near-critical state of slip. Small pressure changes in the well could induce slip as evidenced by acoustic emissions. This would result in new fracture porosity and the possibility of fluid and mud swap-out, followed by thermal effects that made well control very difficult.

Consequently, the drilling of the granite section with six inch hole in Habanero #2 used a process known as Managed Pressure Drilling (MPD). MPD is a combination of both conventional overbalanced drilling and under-balanced drilling technology to permit the minimisation of overpressure on the formation without allowing the formation to produce whilst being drilled. A combination of mud weight, equivalent circulation density and surface applied backpressure was used to find the balance point against the reservoir pressure at the first productive fracture that was exposed in the interval. The benefit that it enabled a constant bottom hole pressure to be applied independent of the operation (i.e. drilling, tripping, making connections etc), and permitted a minimisation of the overbalanced state on subsequent fractures that were exposed in the interval.

The MPD system performed well during the drilling of a number of active fractures, including a strongly active fracture at 4,181 m, down to 4,325 m. However at 4,325 m total losses occurred. Slugs of sized (up to 4 mm) calcium carbonate were used as a lost circulation material (LCM) with partial success, but further losses were induced by subsequent drilling attempts. The depth of the fracture at 4,325 m matched within 15 m of a prediction of the depth to a dominant seismically active fracture at 4,254 m in Habanero #1. This was based on the locations of acoustic events in the vicinity of Habanero #2 during the stimulation of Habanero #1 as determined by our seismic and hydraulic experts from Q-con GmbH of Germany.

The well was able to be blind drilled (total loss of cuttings) below this fracture for a distance of 17 m to 4,342 m, but at this depth a drill collar broke 245 m from the drill bit. The ‘fish’ was unable to be retrieved, and after a short drilling suspension, the well was sidetracked out of the casing at a depth of 3,874 m. The sidetrack was completed to a depth of 4,358 m without incident. The active fracture at 4,325 m did not cause problems in the side track, but a fracture intersected a further 5 m deeper at 4,330 m gave rise to slow mud losses of a few barrels per hour. This fracture is interpreted to be the fracture at 4,325 m in the original hole considerably plugged with mud and LCM.

During the mud loss events and pumping of LCM into the fracture at 4,325 m pressure spikes relating to the turning on and off of mud pumps at Habanero #2 were seen on the pressure gauge at Habanero #1. These spikes are shown in Figure B6.10. The spikes prove conclusively that Habanero #2 is in hydraulic communication with the Habanero #1 reservoir. The permeability appears to be excellent thus assuring successful circulation between the two wells during the testing of the system.

Once the rig was released from Habanero #2 on 3 January 2005, testing could commence. In order to first install the master valves two mechanical safety barriers are needed. The first was a back-pressure valve installed in the wellhead, and the second is a retrievable bridge plug set down the well. Unfortunately during attempts to remove the bridge plug using a coil-tubing unit the bridge plug was lost and fell down the well. This plug is not much smaller in diameter than the well and could cause flow impedance if it did not fall all the way to the bottom. Later flow testing indicated this to be the case.

10. CIRCULATION TESTING

The testing of the Habanero reservoir has two main aims - to determine the natural geothermal character of the discovered overpressured system; and to determine the heat exchange capacity of the fracture system between the two wells. The testing was to be divided into three main phases set to take place during 2005. These were:

Diagnostic Phase – a flow test followed by shut-in to determine the capacity of the natural geothermal field, and a short (three-day) circulation test between the two wells.

Enhancement Phase – depending on the results of the Diagnostic Phase the enhancement of the heat exchanger between the two wells, would possibly consist of local stimulation around Habanero #2, dual stimulation of both wells together, attempted diversion of flow from major fractures to minor fractures and/or further intervention in Habanero-1;

Demonstration Phase – A long term circulation test between Habanero #1 and Habanero #2 including tracer testing to prove the longevity of the heat exchanger between the two wells.

The diagnostic phase commenced on 31 March 2005 with the first opening of Habanero #2 to flow with the assistance of the over-pressured conditions. The two-week flow was completed on 8 June 2005. Flow rates of above 20 l/s and surface temperatures up to 210°C were measured, equivalent to 15 MW of thermal power. Logging confirmed a down-hole flowing temperature at the bottom of the casing at 3,870 m of 250°C.

Logging into the open-hole section was commonly hindered and the logging could never prove the depth of the lost bridge plug. However during the flow test it became clear that near-well-bore constriction was hindering flow. Repeated surging of both flow and pressure in a chaotic way provided strong support that the bridge plug was causing the problems, and eventually the well became completely blocked to flow from the main fracture system, even after the use of acid to try to remove calcium carbonate LCM that may have packed around the plug.

Fluid samples were quite similar to those collected during drilling of Habanero #1 before the injection of fresh water, at about 20,000 ppm total dissolved salts. The implication is that there is a large volume of available natural water in the fracture system.

Using Habanero #1 pressure draw-down versus Habanero #2 production volume curves, it is possible to estimate the fluid volume in the highly connected reservoir. Reservoir engineers Q-Con GmbH estimate the fluid volume is approximately 11 million m^3 indicating a high porosity for granite fractures at such high confining pressures.

The final loss of connection to the main fracture system in Habanero #2 and the confirmation of flowing fractures above the main system by logging provided an opportunity to stimulate these upper fractures independently of the main system. Some 7,000 m3 of fresh water was pumped into the upper fracture system and an upper reservoir was enhanced as indicated by 1,249 acoustic emissions. The enhanced upper reservoir occupies a volume between Habanero #1 and Habanero #2 but is not connected to Habanero #1 because it intersects the well behind casing. Future perforation of the casing could be carried out, but it was decided that a re-stimulation from Habanero #1 would be more valuable because it would show that the existing main reservoir could be enlarged as required.

From 6 to 20 September 2005 20,000 m^3 of water was injected into Habanero #1. This resulted in recording more than 16,000 acoustic emissions from the main fracture system of which 6,388 were located. According to these acoustic emission distributions the area previously stimulated grew by more than 50%.

11. COMPLETION OF TESTING WITH NEW WELL

Despite the great success of extending the reservoir during the September 2005 stimulation, the Habanero #2 well bore still remained unconnected to this fracture system. The dropped bridge plug and packing around the plug is clearly the most likely cause.

On this basis, it was decided to carry out a second side-track operation in Habanero #2. This operation used a snubbing unit rather than a drilling rig, and drilling with water rather than heavy drilling mud in a highly under-balanced condition. After drilling problems were encountered, the decision was made to suspend the snub drilling side track in Habanero #2 at the end of June 2006.

Geodynamics is now planning a new well Habanero #3 which will be of 8 ½ inch size. Design and procurement is now in place and the well will be drilled in 2007. This will allow the reservoir testing program to be completed.

12. RESERVOIR MODELLING

Geodynamics has also completed reservoir modelling with assistance of Q-con GmbH. Alternative well layout patterns and spacings have been assessed to model a number of parameters over time, including temperature performance.

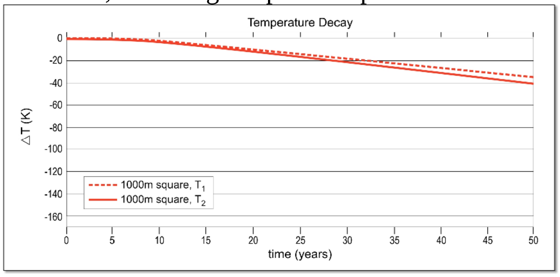

Figure 2. Model of temperature draw-down of an HFR reservoir consisting of a heat exchanger between 4,200 m and 5,000 m depth connected to a well-field of 41 wells arranged in a square pattern. Solid line is the modelled temperature at 5,000 m, dashed line is at 4,200 m. Results of Q-con GmbH.

As shown in Figure 2, Q-con's long-term temperature modelling indicates an approximately 40°C decline after 50 years of operation. This is sensitive to many parameters and is not yet optimised.